

HIGH-ACCURACY HEAT FLOW MEASUREMENT BY USING A QUICK APPROXIMATE ALGORITHM

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Received: Sept. 17, 1998

Abstract

This paper analyzes the problems of heat flow measurement and identifies the parameters the correction of which is necessary to obtain the accuracy specified. The empirical expressions describing the methods of calculating the correction are integrated into a unified system and approximate algorithms are presented that, while ensuring the same accuracy, require significantly less time for the calculation; therefore, in addition to the measuring data acquisition systems used for accounting purposes, they are well suitable to be used in low-power intelligent far-end systems as well.

Keywords: correction heat flow measurement, quick approximate algorithm.

1. Introduction

The extended use and the increasing price of liquid and gaseous primary energy sources resulted in that their measurement with the highest possible accuracy became a significant task in the business practice. Within the measurement of energy sources, the hot water and steam heat energy measurement in addition to the flow measurement is of outstanding importance in our times.

Depending on the specific task, the measurement is aimed at determining the volumetric flow, mass flow and heat flow, respectively, of the media flowing through pipelines. In the industrial practice, the mass flow and heat flow (energy flow) are measured by using deductive methods, which means that they will be determined by means of electronic processing based on volumetric flow measurement corrected by means of the additional measured values of density, pressure, temperature and heating value.

In respect of the industrial penetration, certain authors [1] estimate 80% of volumetric flow meters to be based on throttle elements. In the remaining part, turbine meters share 10% and the vortex, induction, ultrasound and other types also share 10%. Taking the aspects of utilization into account, it can be stated that the use of throttle elements have even higher share in the steam heat flow measurement.

For reasons outlined above, the problems of heat flow and heat energy meters using throttle elements (orifice) as primary sensing elements will be analyzed.

2. Method of Heat Flow Measurement Using Correction

The principle of heat flow measurement by using orifice is shown in *Fig. 1*. In this layout, in addition to the pressure drop across the orifice, the pressure and the temperature of the medium flowing through the pipeline shall also be measured. Based on the values thus measured and using the formulas of correction as detailed in clause 2, the mass flow and the enthalpy of medium can be determined. The product of mass flow and enthalpy results in the heat flow, which shall be integrated for a specific time period to give the heat energy.

3. High-Accuracy Empirical Correction Formulas

The increased demand for determining the heat flow by means of measurement and calculation, respectively, appears from the fact that, as early as during the International Steam Table Conference held in London in 1956, the International Formulation Committee was established, with the aim of developing formulas suitable to calculate the properties of steam that have been described by means of international informative tables so far. The steam research carried out under the coordination of this Committee resulted in the development of an efficient method of calculating the steam parameters (ρ , κ , λ_k , η , h), which is supported by experiments and internationally accepted for accounting purposes.

The symbols used in the formulas described in clauses 3.1 to 3.6 are used here in a consistent manner; therefore, in order to avoid redundant definitions, the symbols together with their meanings are listed below:

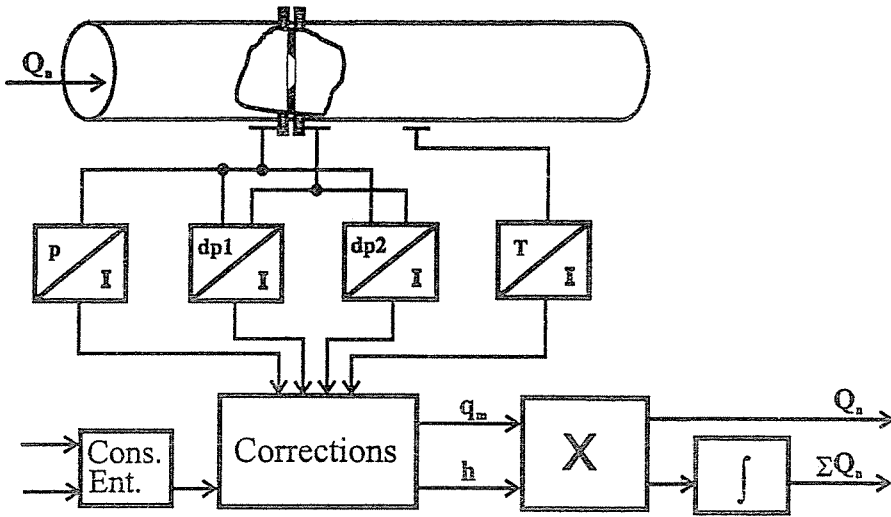


Fig. 1. Principle of heat flow measurement

q_m	mass flow [kg/s]
α	flow coefficient
$\beta = d/D$	ratio of diameters
C	velocity coefficient
d	orifice bore diameter [m]
D	pipe size [m]
dp	pressure difference [Pa]
E	inlet velocity index
ε	expansion coefficient
η	dynamic viscosity [Pas]
h	specific enthalpy
δ	reduced spec. enthalpy
κ	isentropic exponent (p, t dependent)
$\lambda = p/p_K$	reduced pressure
λ_k	reduced saturation pressure
p	operating pressure [bar]
p_S	saturation pressure [Pa]
p_K	critical pressure ($22.12 \cdot 10^6$ Pa)
t	operating temperature [$^{\circ}\text{C}$]
T	operating temperature [K]
T_K	critical temperature (647.3 K)
$\delta = T/T_K$	reduced temperature
ν	specific volume
ν_k	critical specific volume
χ	reduced specific volume
Re	Reynolds number
ρ	density of medium [kg/m^3]

3.1. Calculation of Mass Flow

By using the Bernoulli law and the continuity equation, the relationship between the mass flow and the pressure drop across the orifice can also be deduced analytically. The assumptions made in the deduction (evenly distributed velocity and pressure along the pipe section, incompressible media) are only allowed approximately; therefore by introducing the factors α and ε , the relationship between the mass flow and the pressure difference measured is expressed as follows:

$$q_m = \alpha \cdot \varepsilon \cdot \frac{\pi}{4} \cdot d^2 \cdot \sqrt{2 \cdot dp \cdot \rho}. \quad (1)$$

Considering the factors (ρ , α , ε , d) in the above equation, it can be stated that their value is influenced by the changes in the pressure and temperature of the medium flowing through the pipeline; therefore, in order to obtain higher accuracy of measurement, it is indispensable to measure the pressure and the temperature additionally and to perform the corrections described later in this paper.

3.2. Calculation of Density

The density of medium flowing through the pipeline depends on both the pressure and the temperature. At the given operating point, the density can be determined by direct measurement or it can be calculated from pressure and temperature measurement. For the purpose of calculation, tables or approximative formulas are available. When using the latter method, the density can be calculated by range sections by using different empirical formulas. In the district heating practice, the measurements are carried out in the range section No. 1 and a standardized calculation method is also available for this section [2].

Characteristics of the range section No. 1 are:

$$\delta_t < \delta < \delta_1 \quad \text{and} \quad \lambda_k(\delta) < \lambda < \lambda_2,$$

where δ_t and δ_1 are reduced temperatures associated with 0 °C and 350 °C, respectively, and λ_2 is the reduced pressure associated with 1000 bar.

[2] describes the formulas for the calculation of reduced specific volume which give the density as follows:

$$\rho = \frac{1}{\nu}, \quad (2)$$

$$\nu = \nu_k \cdot \chi. \quad (3)$$

The reduced specific volume in the range section No. 1 will be:

$$\begin{aligned} \chi_1 = \frac{\nu}{\nu_k} = & A_{11}a_5Z^{\frac{-5}{17}} + \left[A_{12} + A_{13}\vartheta + A_{14}\vartheta^2 + A_{15}(a_6 - \vartheta)^{10} + \right. \\ & \left. + A_{16}(a_7 + \vartheta^{19})^{-1} \right] - (a_8 + \vartheta^{11})^{-1} \cdot (A_{17} + 2A_{18}\lambda + 3A_{19}\lambda^2) \\ & - A_{20}\vartheta^{18}(a_9 + \vartheta^2) \cdot \left[-3(a_{10} + \lambda)^{-4} + a_{11} + 3A_{21}(a_{12} - \vartheta)\lambda^2 + \right. \\ & \left. + 4 \cdot A_{22}\vartheta^{-20}\lambda^3 - 3A_{24}\lambda^2\vartheta^{19} \right], \end{aligned} \quad (4)$$

where

$$\begin{aligned} Z &= Y + \left(a_3Y^2 - 2a_4\vartheta + 2a_5\lambda \right)^{\frac{1}{2}}, \\ Y &= 1 - a_1\vartheta^2 - a_2\vartheta^{-6} \end{aligned}$$

and λ represents the reduced pressure and δ is the reduced temperature. The coefficients A_i , a_i used in the formula to calculate the specific volume in the range section No. 1 are shown in the Appendix F1 [2].

3.3. Calculation of the Expansion Factor

For steam, the expansion factor is calculated as follows:

$$\varepsilon = 1 - (0.41 + 0.35 \cdot \delta^4) \cdot dp / (p \cdot \kappa). \quad (5)$$

3.3.1. Calculation of the Isentropic Exponent

The isentropic exponent can be calculated from the expression [2]

$$\kappa = \sum_{J=0}^3 \sum_{k=0}^3 A_{J,k} \cdot t^J \cdot (\ln(p))^k \quad (6)$$

in the temperature range $100 \text{ }^\circ\text{C} \leq t \leq 600 \text{ }^\circ\text{C}$ and the absolute pressure range $1 \text{ bar} \leq p \leq 150 \text{ bar}$. The constant factors $A_{j,k}$ used in the above equation are given in the Appendix F2.

3.4. Calculation of the Flow Coefficient

The flow coefficient is the function of the flow velocity, the density and viscosity of medium, the diameter of pipe and the ratio of diameters. The

first four parameters are related to the Reynolds number while the fifth one is related to the ratio of diameters. The variation of flow coefficient (as a function of flow) can be taken into account by using the formula as follows:

$$\alpha = C \cdot E. \quad (7)$$

3.4.1. Calculation of the Inlet Velocity Index

The inlet velocity index allows the ratio of diameters to be taken into account as follows:

$$E = (1 - \beta^4)^{-0.5}. \quad (8)$$

3.4.2. Calculation of the Velocity Coefficient

The velocity coefficient is the sum of two components, one of which depends on the Reynolds number while the other is independent of the Reynolds number:

$$C = C_0 + C_{Re}. \quad (9)$$

The component C_0 is determined from the geometric parameters of the measuring section and the orifice, depending on the pressure tapping method by means of the formulas below.

Tapping at the corner or ring chamber design:

$$C_0 = 0.5959 + 0.0312 \cdot \beta^{2.1} - 0.184 \cdot \beta^8. \quad (10)$$

D and D/2 pressure taps

$$C_0 = 0.5959 + 0.0312 \cdot \beta^{2.1} - 0.0158 \cdot \beta^3 - 0.184 \cdot \beta^8 + 0.039 \cdot \beta^4 \cdot (1 - \beta^4)^{-1}. \quad (11)$$

Flange taps if $D \leq 58.62$ mm

$$C_0 = 0.5959 + 0.0312 \cdot \beta^{2.1} - 0.0337 \cdot L_2 \cdot \beta^3 - 0.184 \cdot \beta^8 + 0.039 \cdot \beta^4 \cdot (1 - \beta^4)^{-1}. \quad (12)$$

Flange taps if $D > 58.62$ mm

$$C_0 = 0.5959 + 0.0312 \cdot \beta^{2.1} - 0.0337 \cdot L_2 \cdot \beta^3 - 0.184 \cdot \beta^8 + 0.09 \cdot L_1 \cdot \beta^4 \cdot (1 - \beta^4)^{-1}, \quad (13)$$

where: β is the ratio of diameters, L_1 and L_2 are interpreted as follows:

$$L_1 = \frac{l_1}{D}; \quad L_2 = \frac{l'_2}{D},$$

where l_1 represents the distance between the face plate of orifice and the axis of the pressure tap on the high pressure side [m]; while l'_2 represents the distance between the rear plate of orifice and the axis of the pressure tap on the low pressure side.

The component C_{Re} of the velocity coefficient that is the function of Reynolds number is calculated as follows:

$$C_{Re} = 91.71 \cdot \beta^{2.5} \cdot Re^{-0.75}. \quad (14)$$

3.4.3. Calculation of the Reynolds Number

The Reynolds number is expressed as the ratio of the force of inertia acting on the particles of medium to the internal forces of friction. For practical purposes, its value can be calculated from the formula below:

$$Re = \frac{4 \cdot q_m}{\pi \cdot D \cdot \eta}. \quad (15)$$

3.4.4. Calculation of the Dynamic Viscosity

The dynamic viscosity is calculated by using the formula below:

$$\eta_0 = \sqrt{\vartheta} \cdot \left[\sum_{k=0}^3 a_k \cdot \left(\frac{1}{\vartheta} \right)^k \right]^{-1} \cdot 10^{-6}, \quad (16)$$

$$\vartheta = \frac{T}{T_{k1}}; \quad \chi \equiv \frac{\nu}{\nu_{k1}} \quad \text{and} \quad \eta = \eta_0 \cdot \exp \left[\frac{1}{\chi} \sum_{i=0}^4 \sum_{j=0}^5 b_{ij} \cdot \left(\frac{1}{\vartheta} - 1 \right)^i \cdot \left(\frac{1}{\chi} - 1 \right)^j \right],$$

where η_0 is a secondary variable.

The coefficients a_k and b_j used in the calculation of dynamic viscosity are specified in the Appendix F3.

3.5. Correction for Diameters

Among the geometric parameters, the pipe diameter and the bore of orifice are subject to changes as a result of the temperature, which can be taken into account as follows:

3.5.1. Correction According to the Bore Diameter of Orifice

The bore diameter of orifice is determined at some reference (calibration) temperature (usually 20 °C). However, the operating conditions fail to coincide with the reference conditions except a few cases. Under the effect of changes in temperature, the orifice suffers some thermal expansion which can be taken into account by using the formula as follows:

$$d = d_c \cdot [1 + \alpha_d \cdot (T - T_c)], \quad (17)$$

where d_c represents the orifice bore diameter at the temperature of calibration [m], α_d is the linear thermal expansion coefficient [1/K] of the material the orifice is made of and T_c is the temperature of calibration [K].

3.5.2. Correction According to the Pipe Diameter

Again, a similar temperature correction is used by means of the formula as follows:

$$D = D_c \cdot [1 + \alpha_D \cdot (T - T_c)], \quad (18)$$

where D_c [m] is the pipe diameter at the temperature of calibration, α_D is the linear thermal expansion coefficient [1/K] of the pipe material and T_c represents the temperature of calibration [K]. Based on the above equations, the mass flow q_m can be calculated by using iteration. The accuracy depends on the number of iteration cycles.

3.5.3. Calculation of the Specific Enthalpy

For the calculation of heat flow, the specific enthalpy shall be calculated first which, by using the reduced specific enthalpy, is given by the equation below:

$$h = \delta \cdot p_k \cdot \nu_k. \quad (19)$$

The reduced specific enthalpy can be calculated for the range sections specified in the case of density calculation [2]. In the district heating practice, measures are carried out only in the range section No. 1 (the range sections are the same as in the case of density calculation). By using the auxiliary variables

$$\begin{aligned} Y &= 1 - a_1 \cdot \vartheta^2 - a_2 \cdot \vartheta^{-6}, \\ Y' &= -2 \cdot a_1 \cdot \vartheta + 6 \cdot a_2 \vartheta^{-7}, \\ Z &= Y + \left(a_3 \cdot Y^2 - 2 \cdot a_4 \cdot \vartheta + 2 \cdot a_5 \cdot \lambda \right)^{\frac{1}{2}}, \end{aligned}$$

the specific enthalpy δ_i in the first range section can be calculated by using the equation below:

$$\begin{aligned} \delta_1 = & A_0 \cdot \vartheta - \sum_{i=1}^{10} (i-2) \cdot A_i \cdot \vartheta^{i-1} + A_{11} \cdot \left\{ Z \cdot \left[17 \cdot \left(\frac{Z}{29} - \frac{Y}{12} \right) + \right. \right. \\ & \left. \left. + 5 \cdot \vartheta \cdot \frac{Y'}{12} \right] + a_4 \cdot \vartheta - (a_3 - 1) \cdot \vartheta \cdot Y \cdot Y' \right\} \cdot Z^{\frac{-5}{17}} + [A_{12} - A_{14} \cdot \vartheta^2 + \\ & + A_{15} \cdot (9 \cdot \vartheta + a_6) \cdot (a_6 - \vartheta)^9 + A_{16} \cdot (20 \cdot \vartheta^{19} + a_7) \cdot (a_7 + \vartheta^{19})^{-2}] \cdot \lambda - \\ & (12 \cdot \vartheta^{11} + a_8) \cdot (a_8 + \vartheta^{11})^{-2} \cdot (A_{17} \cdot \lambda + A_{18} \cdot \lambda^2 + A_{19} \cdot \lambda^3) + \\ & A_{20} \cdot \vartheta^{18} \cdot (17 \cdot a_9 + 19 \cdot \vartheta^2) \cdot [(a_{10} + \lambda)^{-3} + a_{11} \cdot \lambda] + A_{21} \cdot a_{12} \cdot \lambda^3 + \\ & 21 \cdot A_{22} \cdot \vartheta^{-20} \cdot \lambda^4 + 18 \cdot (A_{23} + A_{24} \cdot \lambda^3) \cdot \vartheta^{19}. \end{aligned} \quad (20)$$

The coefficients used for the calculation of the specific enthalpy in the first range section are the same as those used in the formulas to calculate the specific volume in the first range section (see Appendix F1).

3.5.4. Calculation of the Saturation Curve

The orifice-type flow meters can only be used to measure materials of state the physical condition of which remains unchanged along the measuring section; i.e. the medium remains homogeneous.

In the case of steam measurement, this means that the medium shall always be in superheated phase which shall be verified during the measurement. Within the range of saturation, the density of steam differs from that of water to a significant extent although being both of the same pressure and temperature. The set of related pressure-temperature values forms the saturation curve. The appropriate $p - T$ values are calculated as follows:

$$\lambda_k(\vartheta) = \exp \left[\frac{1}{\vartheta} \cdot \frac{\sum_{i=1}^5 k_i \cdot (1 - \vartheta)^i}{1 + k_6 \cdot (1 - \vartheta) + k_7 \cdot (1 - \vartheta)^2} - \frac{1 - \vartheta}{k_8 \cdot (1 - \vartheta)^2 + k_9} \right]. \quad (21)$$

The values of coefficients used in the above equation are specified in the Appendix F4.

3.6. Calculation of the Steam Heat Flow

The heat flow is given by the product of the mass flow and the specific enthalpy:

$$\begin{aligned} Q_n &= q_m \cdot h && \text{if } p > p_{\text{sat}}, \\ Q'_n &= 0 && \text{if } p < p_{\text{sat}}, \end{aligned} \quad (22)$$

where Q'_n is the water heat flow [W].

The corrections described in clauses 3.1 and 3.6 enable the parameters ρ , α , ε and d to be determined for each measuring cycle in their operating state and, by using these parameters, the mass flow and the heat flow to be calculated with high accuracy. A disadvantage of using these relationships is that, due to the complicated corrections, the time of calculation is significantly increased. For example, the corrections described above take more than ten seconds even by using 8-bit processors that can be considered to be typical in the case of far-end systems. Due to the frequent variation of heat flow, this excessive calculation time may result in measuring errors that are unacceptable in systems used for accounting purposes.

Basically, the time of calculation can be decreased in two ways:

- by using processors of higher performance,
- by elaborating quick approximative methods for the calculation of correction.

By using high-performance processors, the performance/price ratio of the equipment would be decreased, thus, the marketability reduced. The solution is the use of quick approximative algorithms; although, it shall be also noted that the technical development results in a significant decrease in the hardware prices.

4. Quick Approximate Correction Algorithms

In the development of the algorithms, the aspects described below were taken into consideration.

- The measuring accuracy of data processing units used for accounting purposes shall be 0.1%. Considering that the highest accuracy of analogous input devices is 0.05%, the maximum permissible error due to the approximation shall not exceed 0.05%.
- The range of application of the approximate equations shall only cover the measuring range that is usual in the district heating practice ($130\text{ °C} < t < 350\text{ °C}$; $2.8\text{ bar} < p < 30\text{ bar}$).
- Due to its complexity, the approximation shall cover only the calculation of density, enthalpy, dynamic viscosity, the isentropic exponent and the pressure of saturation.

- With the simplicity of algorithm to be used in view, the ranges of validity shall be the same as far as possible.
- In order to reduce the time of calculation, the polynomial used for approximation shall be the lowest possible degree.

4.1. Formulas Used for Approximate Calculation

The degree and coefficient of polynomials used for approximation were determined by using multivariable interactive regression procedures.

Thus, for the purpose of determining the enthalpy, dynamic viscosity, isentropic exponent and the pressure of saturation, the measuring range is divided into 10 range sections (Fig. 2). In each range section, the formulas used for approximate calculation are of the same structure, except the density coefficients that are different in each range section.

Description of the constant values of approximate algorithms for each range section is far beyond the scope of this paper; therefore, we must be content with presenting the constants used for the calculation of the range section No. 3 only for demonstration purposes.

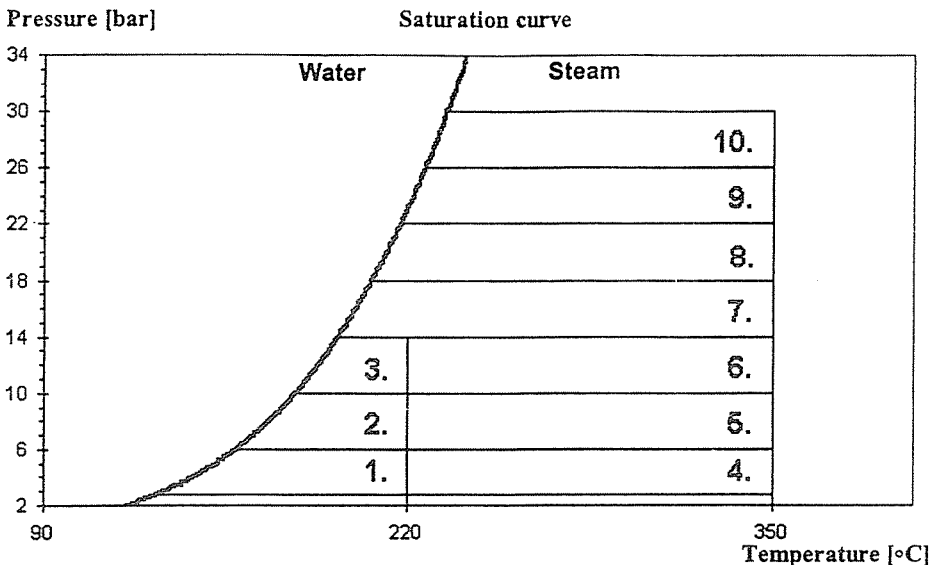


Fig. 2. Dividing the measuring range in the case of enthalpy, dynamic viscosity and isentropic exponent

Approximate calculation of the *enthalpy*:

$$h = H_0 + H_1 \cdot p + H_2 \cdot t + H_3 \cdot p \cdot t + H_4 \cdot p \cdot t^2 + H_5 \cdot p \cdot t^3 + H_6 \cdot p^2, \quad (23)$$

where:

$$\begin{aligned} H_0 &= 2.5256634 \cdot 10^{+3}, & H_1 &= -4.5150032 \cdot 10^{+1}, & H_2 &= 1.7768240 \cdot 10^0, \\ H_3 &= 4.033551 \cdot 10^{-1}, & H_4 &= -1.3363903 \cdot 10^{-3}, & H_5 &= 1.6522029 \cdot 10^{-6}, \\ H_6 &= -6.9274638 \cdot 10^{-2}. \end{aligned}$$

Approximate calculation of the *isentropic exponent*:

$$k = K_0 + K_1 \cdot p + K_2 \cdot t + K_3 \cdot p \cdot t + K_4 \cdot p \cdot t^2 + K_5 \cdot p \cdot t^3, \quad (24)$$

where:

$$\begin{aligned} K_0 &= 1.3455851 \cdot 10^0, & K_1 &= -6.0543134 \cdot 10^{-3}, & K_2 &= -1.4655924 \cdot 10^{-4}, \\ K_3 &= 3.3043807 \cdot 10^{-5}, & K_4 &= -6.1181070 \cdot 10^{-8}, & K_5 &= 4.1887605 \cdot 10^{-11}. \end{aligned}$$

Approximate calculation of the *dynamic viscosity*:

$$h = E_0 + E_1 \cdot p + E_2 \cdot t + E_3 \cdot p \cdot t + E_4 \cdot p \cdot t^2 + E_5 \cdot p \cdot t^3, \quad (25)$$

where:

$$\begin{aligned} E_0 &= 1.6140973 \cdot 10^{-4}, & E_1 &= -2.7575610 \cdot 10^{-6}, & E_2 &= 4.7082063 \cdot 10^{-7}, \\ E_3 &= 2.3885254 \cdot 10^{-8}, & E_4 &= -7.6746672 \cdot 10^{-11}, & E_5 &= 8.9040829 \cdot 10^{-14}. \end{aligned}$$

Approximate calculation of the *pressure of saturation*:

$$p_t = G_0 + G_1 \cdot t + G_2 \cdot t^2 + G_3 \cdot t^3 + G_4 \cdot t^4, \quad (26)$$

where:

$$\begin{aligned} G_0 &= -3.7930172 \cdot 10^{-1}, & G_1 &= 5.1527738 \cdot 10^{-3}, & G_2 &= 8.6032999 \cdot 10^{-5}, \\ G_3 &= -1.4150595 \cdot 10^{-6}, & G_4 &= 1.4237463 \cdot 10^{-8}. \end{aligned}$$

For the approximate calculation of the density, the measuring range was divided into 10 sections as shown in *Fig. 3*.

For the approximate calculation of *density*, the formula below is used:

$$r = R_A + R_0 + R_1 \cdot p^2 + R_2 \cdot p^3 + R_3 \cdot p^4 + R_4 \cdot \frac{p^2}{t} + R_5 \cdot \frac{p^3}{t^2} + R_6 \cdot \frac{p^4}{t^3}, \quad (27)$$

where:

$$R_A = \frac{10^5}{461,51} \cdot \frac{p}{t + 273,16}$$

and

$$\begin{aligned} R_0 &= -9.9300830 \cdot 10^{-5}, & R_1 &= -3.4183870 \cdot 10^{-3}, & R_2 &= -1.2009651 \cdot 10^{-5}, \\ R_3 &= -2.2760880 \cdot 10^{-6}, & R_4 &= 2.2524051 \cdot 10^0, & R_5 &= 1.8722677 \cdot 10^0, \\ R_6 &= 2.4255873 \cdot 10^1. \end{aligned}$$

In the expressions, the temperature t shall be in °C and the pressure p in bar.

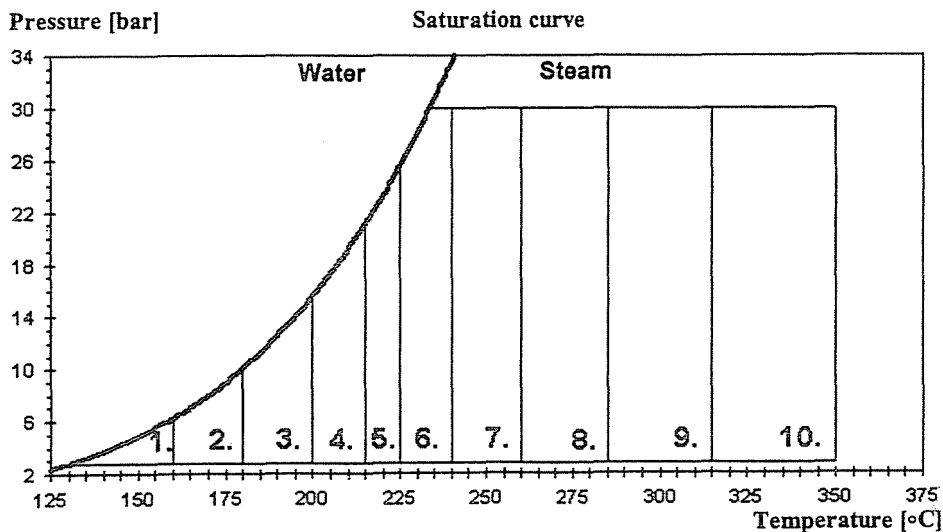


Fig. 3. Dividing the measuring range for the calculation of density

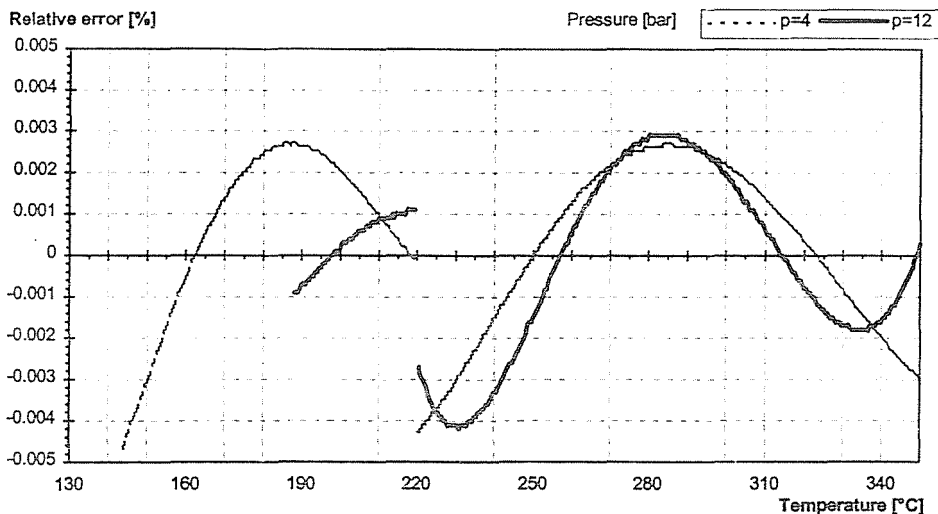


Fig. 4. Error of approximate enthalpy calculation

4.2. Accuracy and Speed of the Approximate Algorithms

In order to estimate the accuracy of the approximate algorithms, the values were calculated by using both the original and the approximate algorithms for each range and the relative errors thus calculated were also represented graphically as a function of temperature (with various pressure values used

as parameters). As an example, *Fig. 4* shows the errors of approximate enthalpy calculation and *Fig. 5* represents the relative errors of heat flow calculation performed by using the approximate algorithms. As shown in the diagrams, the relative error remains below 0.02%.

In respect of the speed of the algorithms, the average time of calculating the corrected heat flow by using the approximate algorithms described above and programmed for the above mentioned 8-bit processor was found to be 500 ms, i.e. twenty times faster than that by using the traditional method described in clause 3.6.

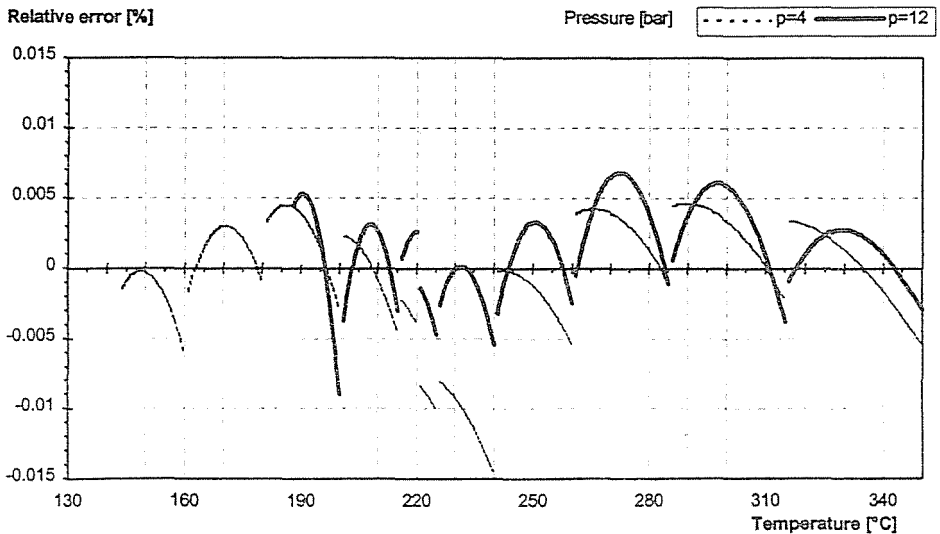


Fig. 5. Error of approximate heat flow calculation

5. High Accuracy Heat Flow Measurement by Using Quick Approximate Algorithms

The high accuracy heat flow calculation algorithm also suitable to be used for accounting purposes is shown in *Fig. 6*. As shown in the flow chart, the mass flow is calculated by means of iteration; therefore, the time of calculation largely depends on the number of iteration cycles. In order to obtain the 0.01% accuracy of calculation set as an objective, the number of iteration cycles does not exceed 3 according to the results of experiments.

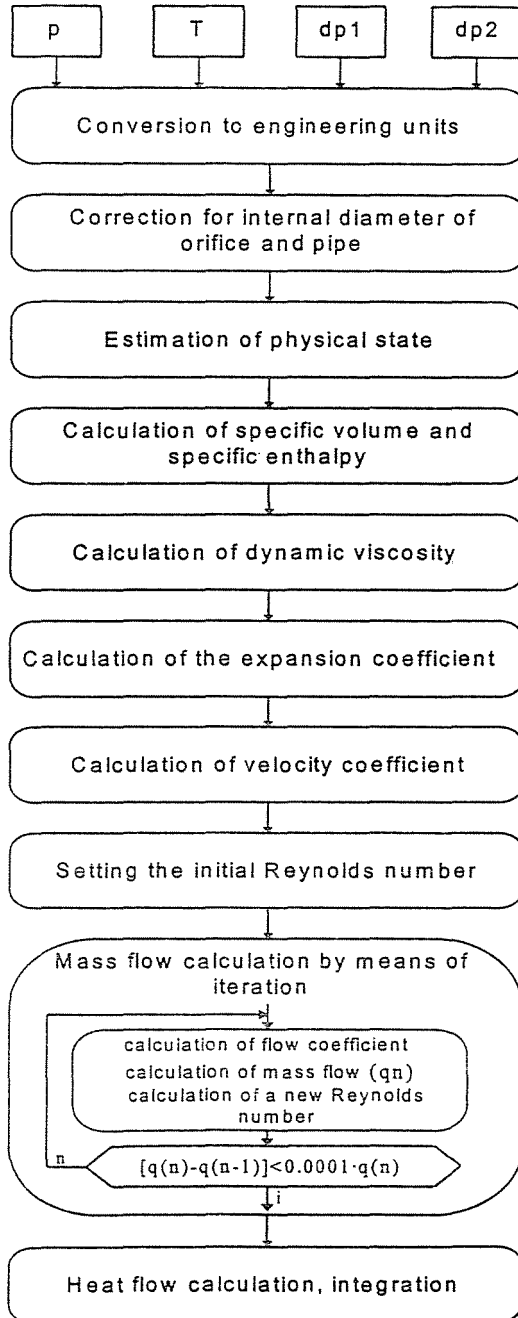


Fig. 6. Heat flow calculation algorithm

6. Conclusions

The approximate algorithms are well suitable to be used in the development of signal processing units and intelligent transmitters of high accuracy measuring systems used for accounting purposes.

The algorithms described in this paper were used in the data acquisition system developed in two versions, i.e. PRODAT-01 with several measuring loops and PROCOR-2 with a single measuring loop [7], both used for steam heat energy accounting and put into service with Budapest Power Plants Ltd.

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Appendix F1. Coefficients of the equation used for the calculation of specific volume within the range section No. 1.

$$\begin{aligned}
 A_0 &= 6.824687741 \cdot 10^3 & A_{13} &= 1.522411790 \cdot 10^{-3} & a_1 &= 8.438375405 \cdot 10^{-1} \\
 A_1 &= -5.422063673 \cdot 10^2 & A_{14} &= 2.284279054 \cdot 10^{-2} & a_2 &= 5.362162162 \cdot 10^{-4} \\
 A_2 &= -2.096666205 \cdot 10^4 & A_{15} &= 2.421647003 \cdot 10^2 & a_3 &= 1.720000000 \cdot 10^0 \\
 A_3 &= 3.941286787 \cdot 10^4 & A_{16} &= 1.269716088 \cdot 10^{-10} & a_4 &= 7.342278489 \cdot 10^{-2} \\
 A_4 &= -6.733277739 \cdot 10^{-4} & A_{17} &= 2.074838328 \cdot 10^{-7} & a_5 &= 4.975858870 \cdot 10^{-2} \\
 A_5 &= 9.902381028 \cdot 10^4 & A_{18} &= 2.174020350 \cdot 10^{-8} & a_6 &= 6.537154300 \cdot 10^{-1} \\
 A_6 &= -1.093911774 \cdot 10^5 & A_{19} &= 1.105710498 \cdot 10^{-9} & a_7 &= 1.150000000 \cdot 10^{-6} \\
 A_7 &= 8.590841667 \cdot 10^4 & A_{20} &= 1.293441934 \cdot 10^1 & a_8 &= 1.510800000 \cdot 10^{-5} \\
 A_8 &= -4.511168742 \cdot 10^4 & A_{21} &= 1.308119072 \cdot 10^{-5} & a_9 &= 1.418800000 \cdot 10^{-1} \\
 A_9 &= 1.418138926 \cdot 10^4 & A_{22} &= 6.047626338 \cdot 10^{-14} & a_{10} &= 7.002753165 \cdot 10^0 \\
 A_{10} &= -2.017271113 \cdot 10^3 & A_{23} &= 2.751372150 \cdot 10^{-3} & a_{11} &= 2.995284926 \cdot 10^{-4} \\
 A_{11} &= 7.982692717 \cdot 10^0 & A_{24} &= 3.458158250 \cdot 10^{-5} & a_{12} &= 2.040000000 \cdot 10^{-1} \\
 A_{12} &= -2.616571843 \cdot 10^{-2} & & & &
 \end{aligned}$$

Appendix F2. Constants for calculation of isentropic exponent

$$\begin{aligned}
 A_{0,0} &= 1.32795 \cdot 10^0 & A_{2,0} &= -1.95743 \cdot 10^{-7} \\
 A_{0,1} &= 1.32470 \cdot 10^{-2} & A_{2,1} &= 8.77604 \cdot 10^{-7} \\
 A_{0,2} &= -6.13619 \cdot 10^{-3} & A_{2,2} &= -6.16351 \cdot 10^{-7} \\
 A_{0,3} &= -3.21479 \cdot 10^{-3} & A_{2,3} &= 7.15009 \cdot 10^{-8} \\
 A_{1,0} &= -4.75238 \cdot 10^{-5} & A_{3,0} &= 1.67223 \cdot 10^{-10} \\
 A_{1,1} &= -2.55307 \cdot 10^{-4} & A_{3,1} &= -8.06485 \cdot 10^{-10} \\
 A_{1,2} &= 1.70119 \cdot 10^{-4} & A_{3,2} &= 5.76494 \cdot 10^{-10} \\
 A_{1,3} &= -8.02514 \cdot 10^{-6} & A_{3,3} &= -8.04816 \cdot 10^{-11}
 \end{aligned}$$

Appendix F3. Constants for the calculation of dynamic viscosity

$a_0 =$	0.0181583	$b_{21} =$	-0.743539
$a_1 =$	0.0177624	$b_{22} =$	-0.959456
$a_2 =$	0.0105287	$b_{23} =$	-0.687343
$a_3 =$	-0.0036744	$b_{24} =$	-0.497089
$b_{00} =$	0.501938	$b_{25} =$	0.195286
$b_{02} =$	-0.130356	$b_{30} =$	0.145831
$b_{03} =$	0.907919	$b_{32} =$	0.347247
$b_{01} =$	0.162888	$b_{33} =$	0.213486
$b_{04} =$	-0.551119	$b_{30} =$	0.263129
$b_{05} =$	0.146543	$b_{34} =$	0.100754
$b_{10} =$	0.235622	$b_{35} =$	-0.032932
$b_{11} =$	0.789393	$b_{40} =$	-0.0270448
$b_{12} =$	0.673665	$b_{41} =$	-0.0253093
$b_{13} =$	1.207552	$b_{42} =$	-0.0267758
$b_{14} =$	0.0670665	$b_{43} =$	-0.0822904
$b_{15} =$	-0.0843370	$b_{44} =$	0.0602253
$b_{20} =$	-0.274637	$b_{45} =$	-0.0202595

Appendix F4. Constants for the calculation of the saturation curve

$k_1 =$	$-7.691243564 \cdot 10^0$
$k_2 =$	$-2.608023696 \cdot 10^1$
$k_3 =$	$-1.681706546 \cdot 10^2$
$k_4 =$	$6.423285505 \cdot 10^1$
$k_5 =$	$-1.189646225 \cdot 10^2$
$k_6 =$	$4.167117320 \cdot 10^0$
$k_7 =$	$2.097506760 \cdot 10^0$
$k_8 =$	109
$k_9 =$	6